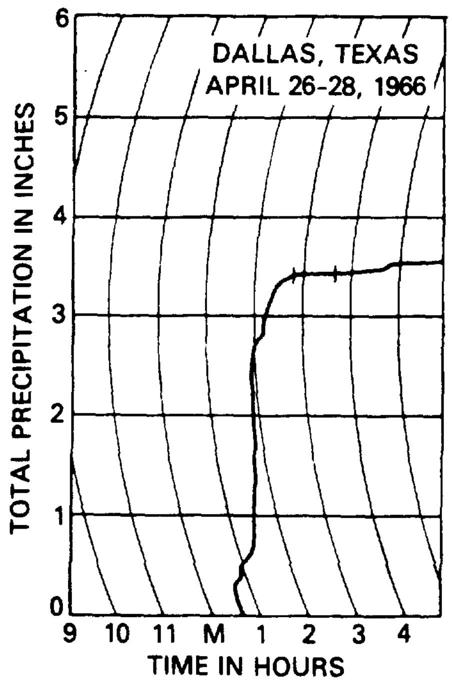
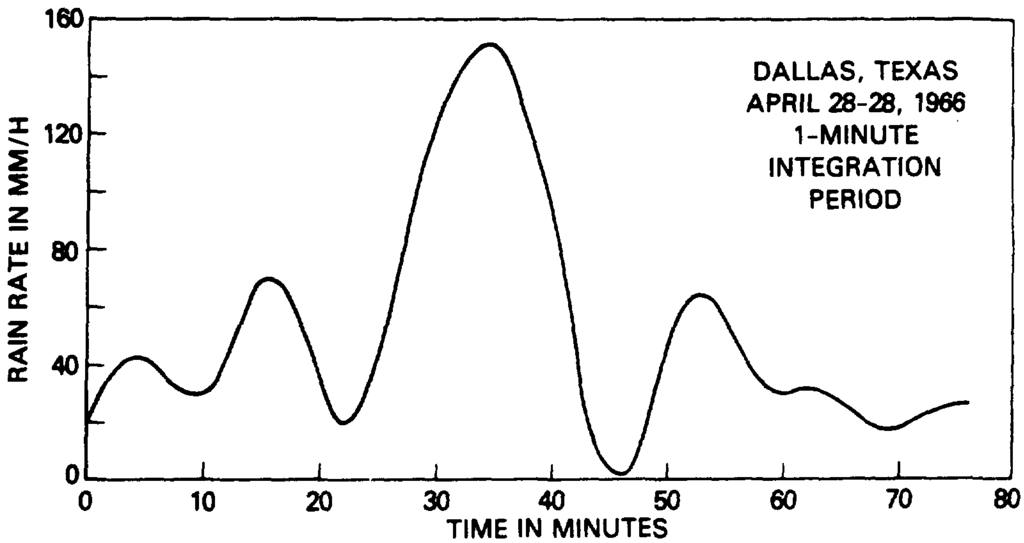


a) National Weather Service Weighing Gauge Chart



b) Rain Rates vs. Time Computed From Weighing Gauge Data

Figure 2.4-8. An Example of Generation of Rain Rate Data From a Weighing Gauge Chart

The data in the Monthly Records (available about four months following recording) is of most importance to the earth space path engineer. As shown in Figure 2.4-9, the rainfall, snowfall and total precipitation are given for each day of the month. The Monthly Summary table indicates the number of thunderstorms, etc., and the recording rain gauge data for selected cities is given. These are the maximum amounts for the duration periods indicated on the date of occurrence. In addition, the number of hourly periods with rainfall accumulations between 0.01-0.09, 0.1-0.19, etc., inches is noted. These data are obtained from tipping bucket rain gauges measuring in increments of 0.01 inches.

The tipping bucket rain gauge data is available for many more Canadian locations. The charts from these gauges are available upon request from the Climatological Recording Services Branch of the Head Office in Downsview, Ontario, at a nominal charge.

2.4.3 Worldwide Sources

Many countries prepare meteorological data similar to the U.S. and Canada. Many of these are on file at the National Weather Service Library, Room 816, Gramax Bldg., 13th Street, Silver Spring, MD. One document, the Monthly Climatic Data for the World, does list the number of days per month a station receives more than 1 mm of rain and the total rainfall per month. The data is coarse and can only provide a general indication of the precipitation climate. An example is shown in Figure 2.4-10. This document was discontinued with the December 1980 issue, but back issues are available for $4.20 per monthly copy from the National Climatic Center.

2.5 ESTIMATION OF RAIN RATE

The rain rate measurement is an inexact process because of the discrete nature of rainfall. Obviously, because rain falls as raindrops, the rain rate is computed by measuring the rain accumulation per given area for a known period of time at a point. The shortest period of time reported by the U.S. and Canadian

TABLE/TABLEAU 2 **PRECIPITATION** MARCH 1977 MARS

STATION		TOTAL	% OF NORMAL / % DE LA NORMALE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	∴
ONTARIO ONTARIO																																			
OTTAWA BRITANNIA	R/F	[illegible]					2.3	1.0							1.5	[illegible]	2.5	1.0													7.4	1.3	1.5		
	S/N	[illegible]			T																		0.5	0.3	[illegible]										
	P	[illegible]			T		2.3	1.0							1.5	[illegible]	2.6	1.0					0.5	0.3	[illegible]						7.4	1.3	1.0		
OTTAWA CDA	R/F	[illegible]	[illegible]				2.8	1.3							0.8	17.0	5.1	3.6						0.3							6.4	0.3	1.0		
	S/N	[illegible]	[illegible]	T	T		T	0.3	T	T										T			1.0	0.5	[illegible]	0.5									[illegible]
N	P	[illegible]	[illegible]	T	T		2.8	1.5	T	T					0.8	17.0	5.1	3.6		T			1.0	0.8	[illegible]	0.5					6.4	0.3	1.0		
OTTAWA INT'L A	R/F	70.1	[illegible]				9.4	0.4							T	[illegible]	12.5	T	1.0					0.2							6.5	1.4	1.4		
	S/N	[illegible]	77	T	T		0.5	1.2	T	T										T			1.1	T	21.5	2.0									[illegible]
N	P	[illegible]	[illegible]	T	T		[illegible]	1.6	T	T					T	[illegible]	12.5	T	1.0	T			1.1	0.2	[illegible]	2.7					6.5	1.4	1.4		
OTTAWA NRC	R/F	[illegible]	[illegible]				11.7									[illegible]	4.1	2.5	0.3												10.2		2.5		
	S/N	[illegible]	[illegible]					T		T													[illegible]		[illegible]										[illegible]
	P	[illegible]	[illegible]				11.7	T		T						[illegible]	4.1	2.5	0.3				[illegible]		[illegible]						10.2		2.5		

[illegible]

MARCH 1977 MARS **RECORDING RAIN GAUGE DATA/ DONNEES DES PLUVIOGRAPHES** TABLE/TABLEAU 7

STATION		MAXIMUM AMOUNTS (.01 inch) HAUTEUR MAXIMUM (en .01 de pouce) FOR DURATION INDICATED WITH DATES OF OCCURENCE POUR LES DUREES MENTIONEES ET DATES																HOURLY RAINFALL CHUTE DE PLUIE HORAIRE No. of occurrence in classes shown Frequence par classe					
		5 min.		10 min.		15 min.		30 min.		60 min.		120 min.		6 hr.		12 hr.							
		AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	.01–.09	.10–.19	.20–.49	.50–.99	1.00–1.99	2.00 or more ou plus
ONTARIO ONTARIO																							
OTTAWA INT'L A		04	30	05	04	08	13	13	13	19	04	32	13	78	13	111	13	46	11				
SAULT STE MARIE A		04	12	05	12	08	12	15	12	27	12	35	12	71	12	77	12	43	6	3			
SIMCOE		06	04	11	12	15	12	25	12	32	12	49	12	103	12	129	12	40	6	2			
SIOUX LOOKOUT A	*	02	27	03	27	04	27	08	27	13	27	13	27	14	27	14	27	3					
SUDBURY A	*	M		M		M		M		M		M		M		M		M	M				

MARCH 1977 MARS **MONTHLY SUMMARY**

STATION	NUMBER OF DAYS WITH / NOMBRE DE JOURS AVEC										
	TEMPERATURES < 0.0°C	THUNDERSTORMS ORAGES	RAIN OR DRIZZLE PLUIE OU BRUINE	FREEZING PRECIPITATION PRECIPITATIONS SE CONGELANT	HAIL GRELE	SNOW NEIGE	MEASURABLE PRECIPITATION PRECIPITATION MESURABLE	FOG BROUILLARD	SMOKE OR HAZE FUMEE OU BRUME SECHE	DUST OR BLOWING SAND POUSSIERE OU CHASSE SABLE ELEVEE	BLOWING SNOW CHASSE NEIGE ELEVEE
ONTARIO											
NORTH BAY A	24	1	6	1		7	12	5	1		
OTTAWA INT'L A	22	1	8	1		5	12	11	8		1
PETAWAWA A	27	1	8	1		4	10	5	4		
PETERBOROUGH A	28	2	6	1		5	12	2	6		1
PICKLE LAKE	31		3	3		10	12	3			1

Figure 2.4-9. Examples of the Canadian Monthly Record Precipitation Data

SURFACE DATA

OCTOBER 1977

STATION	LATITUDE	LONGITUDE	ELEVATION	NUMBER OF DAYS OF OBSNS.	PRESSURE		TEMPERATURE		VAPOR PRESSURE		PRECIPITATION				SUN-SHINE
					MEAN STATION	MEAN SEA LEVEL	MEAN	DEPARTURE	MEAN	DEPARTURE	NO. OF DAYS ≥ 1 MM.	TOTAL	DEPARTURE	QUINTILE	PERCENTAGE OF LONG-TERM AVERAGE
	° ′	° ′	METERS		MB	MB	°C	°C	MB	MB		MM	MM		%
CANADA-EASTERN															
ALERT	82 30 N	62 20 W	63	31	1003.7	1012.2	-18.9	+ 0.9	1.1	-0.1	4	9	- 7		
EUREKA	80 00 N	85 56 W	10	31	1008.5	1009.9	-21.0	+ 0.5	1.2	+0.1	1	4	- 3		
RESOLUTE	74 43 N	94 59 W	67	31	998.0	1006.9	-14.3	+ 0.3	2.1	+0.2	6	22	+ 6		106
CLYDE	70 27 N	68 33 W	6	31	1002.1	1005.4	- 7.6	- 1.2	3.2	-0.3	11	55	+ 21		
HALL BEACH	68 47 N	81 15 W	8	31	1004.9	1005.8	- 9.4	+ 1.6	3.0	+0.2	9	27	+ 4		
BAKER LAKE	64 18 N	96 00 W	13	31	1007.0	1008.6	- 5.1	+ 2.4	4.0	+0.5	10	57	+ 37		
CORAL HARBOUR	64 12 N	83 22 W	64	31	999.0	1007.3	- 5.8	+ 2.2	3.9	+0.4	16	46	+ 17		
FROBISHER BAY	63 45 N	68 33 W	34	31	1002.3	1006.7	- 3.8	+ 0.9	4.0	+0.2	13	52	+ 18		97
CHURCHILL	58 45 N	94 04 W	29	31	1005.5	1009.1	2.5	+ 3.6	5.7	+0.6	6	23	- 15		142
INOUCDJOUAC	58 27 N	78 07 W	5	31	1008.1	1008.7	1.7	+ 2.1	6.3	+0.7	14	71	+ 22	5	131
FORT CHIMO	58 06 N	68 25 W	37	31	1004.4	1009.1	0.1	+ 0.4	5.4	+0.2	12	48	+ 9		
TROUT LAKE	53 50 N	89 52 W	220	31	987.0	1014.2	4.9	+ 3.1	6.2	-0.1	5	47	- 6		
NITCHEQUON	53 12 N	70 54 W	536	31	948.7	1014.0	0.9	+ 0.3	5.7	0.0	13	64	- 16		
MOOSONEE	51 16 N	80 39 W	10	31	1013.4	1014.7	5.3	+ 1.4	6.8	-0.4	6	58	- 15		173
ARMSTRONG	50 17 N	88 54 W	323	31			4.1	+ 1.0			5	34	- 25		147
KAPUSKASING	49 25 N	82 28 W	227	31	998.4	1016.5	4.3	- 0.3	6.5	-0.8	9	69	- 3		
GERALDTON	49 42 N	86 57 W	331			U									
SEPT-ILES	50 13 N	66 16 W	55	31	1006.6	1013.4	4.8	+ 0.9	6.5	-0.2	14	157	+ 74		107
GOOSE	53 19 N	60 25 W	49	31	1005.2	1011.3	3.2	0.0	5.9	-0.1	10	78	+ 15		102
NORTH BAY	46 22 N	79 25 W	371	31	972.4	1017.4	5.4	- 1.2	7.2	-1.0	9	62	- 22		128
MANIWAKI	46 23 N	75 58 W	170	31	995.8	1016.7	5.8	- 1.1	7.2	-0.9	9	63	- 5		106
TORONTO/MALTON INT AP	43 41 N	79 38 W	173	31	996.2	1017.3	8.0	- 1.5	8.5	-1.1	6	69	+ 10		
MONTREAL/DORVAL INT AP	45 28 N	73 45 W	36	31	1011.6	1016.0	7.6	- 1.4	8.5	-0.4	11	113	+ 35		
BAGOTVILLE	48 20 N	71 00 W	159	31	995.6	1015.2	5.6	- 0.1	6.7	-0.6	10	61	- 2		
CHATHAM	47 01 N	65 27 W	34	31	1009.6	1013.7	7.2	- 0.2	8.1	-0.2	16	257	+174	5	87
STEPHENVILLE	48 32 N	58 33 W	26	31	1009.6	1012.8	7.8	+ 0.6	8.4	0.0	17	183	+ 84		
GANDER INT AP	48 57 N	59 34 W	151	31	993.8	1012.4	6.3	0.0	8.1	+0.1	14	127	+ 26		90
SHEARWATER	44 38 N	63 30 W	51	31	1008.7	1015.0	9.8	+ 0.2	10.2	0.0	13	142	+ 33		108
SYDNEY	46 10 N	60 03 W	62	31	1006.8	1014.4	8.7	- 0.4	8.7	-1.1	13	130	+ 15	4	70
SHELBURNE	43 43 N	65 15 W	30			U									
SABLE ISLAND	43 56 N	60 01 W	4	31	1015.4	1015.9	11.7	+ 0.1	11.7	0.0	14	122	+ 12	4	70
ST. JOHN'S (TORBAY)	47 37 N	52 45 W	141			U									
ST PIERRE AND MIQUELON															
ST PIERRE	46 46 N	56 10 W	5	31	1013.9	1014.5	9.1	+ 0.2	9.8	+0.4	13	87	- 50	1	112
UNITED STATES-NORTHEAST															
INTERNATIONAL FALLS	48 34 N	93 23 W	361	31	975.0	1016.7	6.3	- 0.1				20	- 23		
DULUTH	46 50 N	92 11 W	432	31	975.4	1017.3	6.8	- 0.6				81	+ 23		104
ST. CLOUD	45 35 N	94 11 W	318	31	979.0	1017.6	7.8	- 0.9							
SAULT STE. MARIE	46 28 N	84 22 W	221	31	993.8	1016.8	7.1	- 0.8	8.1	0.0	8	47	- 25	2	81
BURLINGTON	44 28 N	73 09 W	104	31	1001.8	1016.6	8.1	- 1.2	8.2		10	128	+ 58	5	88
CARIBOU	46 52 N	68 01 W	146	31	991.5		6.4	- 0.2				135	+ 51		
DES MOINES	41 32 N	93 39 W	294	31	986.8	1018.0	11.3	- 1.1	9.4	-0.2	10	130	+ 75	3	82
COLUMBIA	38 49 N	92 13 W	274	31	990.1	1018.5	13.1	- 1.3				112	+ 26		85
CHICAGO	41 47 N	87 45 W	190	31	995.6	1018.3	11.0	- 2.0	8.9	-0.8	9	42	- 24	2	76
ST. LOUIS	38 45 N	90 23 W	172	31	998.3	1018.9	13.1	- 2.0	11.5	+0.7	7	96	+ 25	4	94
DAYTON	39 54 N	84 13 W	306	31	985.8	1018.6	11.0	- 2.1	8.6		9	98	+ 49	5	76
COLUMBUS	40 00 N	82 53 W	254	31	986.5	1018.5	13.1	- 1.3	8.3	-1.9	9	65	+ 17	4	85
BUFFALO	42 56 N	78 44 W	215	31	989.3	1017.5	9.8	- 1.1	9.1	0.0	9	66	- 10	3	91
NEW YORK LA GUARDIA	40 46 N	73 54 W	9	31	1005.4	1016.9	12.7	- 1.8	11.1	-0.3	2	148	+ 73	5	
BOSTON	42 22 N	71 02 W	9	31	1011.4	1016.0	12.9	- 0.1	11.2	+0.6	2	118	+ 41	5	85
BLUE HILL OBS	42 13 N	71 07 W	195	31	992.1	1015.2	10.7	- 1.1	10.6	+0.6	12	163	+ 71	5	89
CHATHAM	41 40 N	69 58 W	16			U									
WASHINGTON DULLES	38 57 N	77 27 W	98			U									
WASHINGTON NATIONAL	38 51 N	77 02 W	20	31	1013.5	1017.8	15.0	- 0.4	11.0	-0.7	7	136	+ 68	5	84

Figure 2.4-10. An Example of the Monthly Climatic Data for the World

Weather Services is five minutes. Assuming the rain rate is uniform for that period of time, the computed point rain rate and the "instantaneous" point rain rate are equal. However, the question arises as to how the apparent rain rate varies as the integration (computing) time is varied. This effect has been addressed experimentally by experimenters at the Bell Telephone Laboratories.

At Holmdel, NJ, measurements (Bodtmann and Ruthroff-1974) of the apparent rain rate versus the gauge integration period over a 2-year period have yielded the results in Figure 2.5-1. These results extend from 1.5 seconds to 2 minutes and are normalized to a one-minute integration time. Unfortunately, the measurement do not extend to a 5-minute integration time which would be very convenient for comparison of the Lin model with other rain models which employ a one-minute integration period (see Chapter 3). The variation between a 2-minute and a 5-minute integration time is expected to be significant for high rain rates. However, Figure 2.5-1 clearly shows that for rain rates below 50 mm/h the error due to the integration time is small. This effect arises because the low rain rate events tend to be spatially and temporally uniform, while the rain rates between 50 and 120 mm/h are dominated by spatially and temporally nonuniform convective rains.

Only the most severe cells create rain rates above 120 mm/h and these are highly variable. Therefore, a significant peak rain rate two or three times as high as the one-minute average can occur for one second during the one-minute period. As an example, a typical rain rate versus time profile comparing the one-minute and ten-second integration times is shown in Figure 2.5-2 (Bodtmann and Ruthroff-1974).

The impact of varying integration times can be significant for both the measurement of cumulative rain rate statistics (related to cumulative attenuation statistics) and rain rate duration measurements (related to attenuation fade duration). Lin (1978) has experimentally determined the effect of the integration time on cumulative statistics. The results for Palmetto, GA are shown in

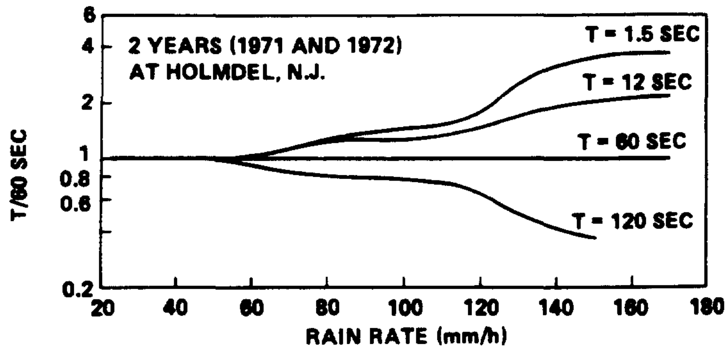


Figure 2.5-1. Rain Rate Distribution Versus Gauge Integration Time

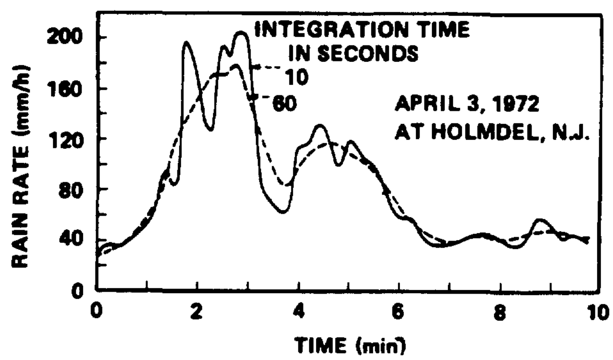


Figure 2.5-2. Integrating Rain Gauge Results for Two Integration Times

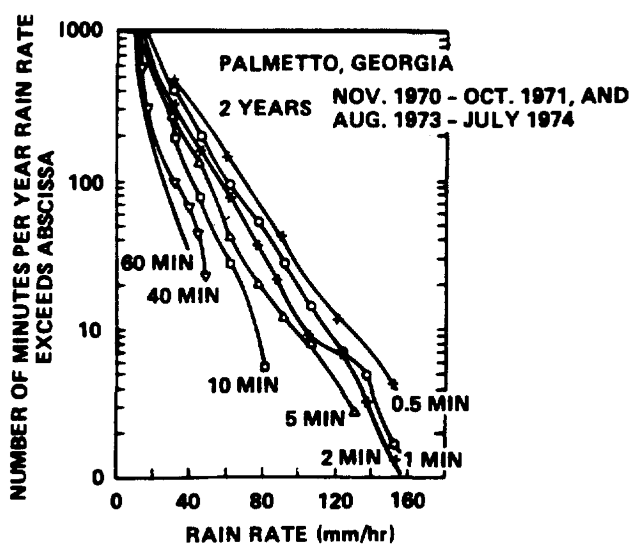


Figure 2.5-3. Cumulative Rain Rate Statistics Versus Integration Period

Figure 2.5-3. Clearly the difference between a 1-minute and 30-second integration time is significant. Similar results for rain rate duration statistics are not available.

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CHAPTER III

AN OVERVIEW OF SEVERAL RAIN AND RAIN ATTENUATION MODELS

3.1 INTRODUCTION

3.1.1 Summary of Models

Several models for estimation of the cumulative attenuation statistics on earth-space millimeter paths have been developed. Each of these models appears to have advantages and disadvantages depending on the specific application. In this chapter an attempt is made to briefly summarize the key features of commonly used models. Chapter VI provides information on the application of these models and includes examples. Many of the models employ the concept of "effective path length," which is explained at the end of this chapter.

Table 3.1-1 summarizes the key inputs, outputs and other important features of seven models in their current format. Nearly all of these models are being updated and modified based on recent experimental results and analyses. In addition, other models prepared by major communications companies, such as Comsat, are utilized (Gray and Brown-1979), but these are generally not published in the open literature and are accordingly omitted here.

The models provide rain rate statistics, attenuation statistics, or both. Generally, these statistics can be related by use of the specific attenuation and effective path length relations. (Specific attenuation is described in Chapter II, while the effective path

Table 3.1-1. Summary of Model Parameters

Model	Inputs	Outputs	Comments
Rice-Homberg	Climate or Site-Specific Mean Annual Rainfall plus Ratio of Thunderstorm-to-Total Rain.	Cumulative Time Distribution of Rainfall.	Two Rain Modes Considered: Thunderstorm & Uniform Rains. Probability of Rain Rate Exceedance for Either or Both Modes is Available.
Dutton-Dougherty	Same as Rice-Homberg and Link Parameters (e.g., Frequency, Elevation Angle).	Rain or Gaseous Attenuation Associated with a Given Exceedance Time Percentage.	Utilizes Modified Rice-Holmberg Rain Model. Provides Confidence Limits, Given Two Additional Rain Rate Distributions.
Global	Location and Link Parameters.	Rain Attenuation Associated with a Given Exceedance Time Percentage.	All Rain Attenuation Parameter Values are Selfcontained. Globally Applicable.
Two-Component	Same as Global.	Exceedance Time Percentage Associated with a Given Rain Attenuation.	Same Rain Model (& Comments) as for Global Model. Two Rain Modes Considered: Convective Cell and Debris Rains.
CCIR	Same as Global.	Rain Attenuation Associated with a Given Exceedance Time Percentage.	All Rain Attenuation Parameter Values are Selfcontained. Globally Applicable.
Lin	Five Minute Rain Rate and Link Parameters.	Attenuation Associated with a Given Rain Rate.	Simple Extension of Terrestrial Path Rain Attenuation Model.
Simple Attenuation (SAM)	Rain Statistics and Link Parameters.	Attenuation Associated with a Given Rain Rate.	Assumes Exponential Shapted Rain Profile.

length concept is summarized at the end of this chapter.) For example, the Rice-Holmberg model only computes the exceedance probability statistics for rain rate, but this is relatable to attenuation by use of the specific attenuation and the effective path length. The Dutton-Dougherty, CCIR, Two-Component, and Global models provide the attenuation statistics given the geographic and link parameters. That is, they give the rain rate statistics within the model.

3.1.2 Concepts of Rainfall Statistics

3.1.2.1 Cumulative Statistics. The cumulative statistics for either rain rate or attenuation are usually presented as the probability of exceedance (abscissa) versus the rain rate or attenuation (ordinate). They represent stable statistics averaged over a period sufficiently long that variations in the lowest frequency component of the time distribution are averaged. For rain rate and rain attenuation the period corresponding to the lowest frequency is generally considered to be one year. Higher frequency components are the seasonal and daily variation of the rain rate. For example, in the eastern US, the higher frequency components arise because more rain falls in the summer than in the winter, and more rain falls between noon and 6 PM than between 6 AM and noon local time. Some people have suggested that the 11-year solar cycle is the lowest frequency component, but this has not been observed by the Weather Service.

Based on the above considerations the cumulative statistics for several years are required before "stable" annual statistics are obtained. For this reason, experimentally generated data bases for both rain and attenuation are not generally good until 5 or 10 years of data are included. However, because of the limited lifetime of the beacon satellites, attenuation data at a known frequency and elevation angle is generally not available for this length of period (Kaul et al-1977). Therefore data from several satellites launched over a long period are required. Since they are not at the same frequency and elevation angle, these results must be scaled in order to be combined. Frequently this process has not been done accurately, resulting in small segments of attenuation data which are not representative of the long term statistics.

Based on the above discussions it appears that the only present recourse is to utilize rain rate data as derivable from Weather Bureau or other long-term measurements. This leads to the exceedance curves or rain rate. The attenuation is then derived from the relations between rain rate and attenuation.

3.1.2.2 Outage Period Statistics. System designers are also interested in the average length of time a given threshold of rain rate or attenuation is exceeded (also termed the outage time). In addition, the distribution of the outage time about the average is desired. Theoretical work of Lin (1973) has shown that the distribution is approximately lognormal.

Besides the outage time, Hyde (1979) has identified the desire to know the average time between outage periods within a given rain event, and the average time between outages between two rain events. The first case recognizes that outages may occur several times during the same general rain event because the rain rate is highly variable during an event. For example, the passage of several rain cells associated with a given rain front may cause several outages as each cell dominates the path attenuation. It is desirable to know the approximate period between these outages and the distribution of these outage periods as a function of attenuation threshold and type of rain event. This type of data is expected to be dependent on the geographic region because the weather fronts are distorted by the presence of mountain ranges, lakes, cities, etc. Therefore, extrapolation to other regions is difficult unless their weather systems are similar.

The second case (average time between outages in two rain events) correlates the period between severe storms in a given region. This period is expected to be seasonally dependent because in most regions the high rain rate storms usually occur during a short period of the year. Again, some statistical estimate of the average period and the distribution of the periods would be desirable.

Generally, outage period data is not as readily available as the cumulative attenuation statistics data. Therefore, the designer must rely on the limited data bases available from CCIR (1986, Rpt 564-3), Comsat (Rogers and Hyde-1979) or Lin (1973, 1980). Vogel (1982) has calculated time-between fade (intermission) statistics for 19 and 28 GHz at Austin, Texas. An estimate of the upper limit of the outage time is presented in Chapter VI.

3.2 RICE-HOLMBERG MODEL

3.2.1 Types of Storms

The Rice-Holmberg (R-H) Model (Rice and Holmberg-1973) is based upon two rainfall types: convective ("Mode 1", thunderstorm) rains and stratiform ("Mode 2", uniform) rains. The statistical model is based upon the sums of individual exponential modes of rainfall rates, each with a characteristic average rate R. According to this descriptive analysis

rainfall = Mode 1 rain + Mode 2 rain

The exponential distribution chosen to describe "Mode 1 rain" corresponds to a physical analysis of thunderstorms, while "Mode 2 rain," represented by the sum of two exponential distributions, is all other rain. In temperate climates only convective storms associated with strong updrafts, high radar tops, hail aloft and usually with thunder can produce the high rainfall rates identified by Mode 1. Only the highest rates from excessive precipitation data are used to determine parameters for Mode 1, which is intended to represent a physical mechanism as well as a particular mathematical form.

3.2.2 Sources of Data

The rainfall statistics in the R-H model are based upon the following:

1) Average year cumulative distributions of hourly rates for the 10 years 1951 to 1960 and for a total of 63 stations, with 49 in the continental U.S. as summarized in the Weather Service Climatological Data for this period;
2) Distributions for 15-year averages with recording intervals of 6, 12, and 24 h for 22 of these stations (Jorgenson, et al-1969);
3) Accumulations of short-duration excessive precipitation for 1951 to 1960 for recording intervals of 5, 10, 15, 20, 30, 45, 60, 80, 100, 120, and 180 min for 48 U.S. stations;
4) A U.S. map of the highest 5-min rates expected in a two-year period (Skerjanec and Samson-1970);
5) Maximum monthly rainfall accumulations and the average annual number of thunderstorm days for the period 1931 to 1960 for 17 U.S. stations and 135 additional stations reported by the World Meteorological Organization.

3.2.3 R-H Model Parameters

The average annual total rainfall depth M is the sum of contributions M_1 and M_2 from the two modes:

$$M = M_1 + M_2 \text{ mm} \tag{3.2-1}$$

and the ratio of "thunderstorm rain" M_1 to total rain M is defined as

$$\beta = M_1/M \tag{3.2-2}$$

The number of hours of rainy t-min periods for which a surface point rainfall rate R is exceeded is the sum of contributions from the two modes:

$$T_t\ (R) = T_{1t}\ q_{1t}(R) + T_{2t}q_{2t}\ (R) \text{ hours}$$

There are 8766 hours per year, so $T_t(R)/87.66$ is the percentage of an average year during which t-min average rainfall rates exceed R mm/h. The data show that the average annual clock t-min rainfall rate for each of the modes is fairly constant. On the other hand, the total number of rainy t-min periods for each mode is relatively much more variable from year-to-year and between stations or climate regions. Rainfall climates defined by Barry and Chorley (1970) for the United States were found to correspond very well with observed regional variations of the parameter β .

The average annual total of t-min periods of Mode 1 and Mode 2 rainfall are T_{1t} and T_{2t}, respectively. The average annual Mode 1 and Mode 2 rainfall rates are therefore

$$\bar{R}_{1t} = M_1/T_{1t} \text{ mm/h} \qquad (3.2\text{-}3)$$

$$\bar{R}_{2t} = M_2/T_{2t} \text{ mm/h}$$

Note that M_1 and M_2 are not functions of t, since the amount of rainfall collected over a long period of time does not depend on the short-term recording interval t. But the total number of hours T_{1t} or T_{2t} of rainy t-min intervals (collecting at least 0.01 in or 0.254 mm of rain per interval) will depend on t.

The factors $q_{1t}(R)$ and $q_{2t}(R)$ are the complements of cumulative probability distributions. Each factor is the number of hours that a rate R is exceeded by Mode 1 or Mode 2 rain divided by the total number of hours, T_{1t} or T_{2t}, that there is more than 0.254 mm of rain in a t-min period.

3.2.4 Time Intervals

The formulas to be presented are for t=1 clock-minute rates. Here clock-minutes are defined as beginning "on the minute" for a continuous t-minute period.

For the more general case where t>1 min, one more prediction parameter is required in addition to the two that have been defined as M and B. This additional parameter is the number of hours of rain per year, D. The formulas proposed here for $q_{1t}(R)$ and $q_{2t}(R)$ assume that the number of rainy days in an average year is

$$D/24 = 1 + M/8 \text{ rainy days} \tag{3.2-4}$$

where D is in hours and M is in millimeters. This relation has been found good, on the average, for continental U.S. stations. A comparison of the cumulative distributions versus the surface rainfall rate R for various values of t from 1 minute to 1 day is shown in Figure 3.2-1. Clearly, for β=0.125 and M=1000mm, the values for t=1 and 5 minutes are nearly equal, but longer periods give a significantly different value for $T_t(R)$.

3.2.5 <u>Model Results for One-Minute Intervals</u>

For t=1, the more general formulas are almost independent of D, so that

$$q_{1t}(R) = \exp(-\bar{R}/R_{1t})$$

$$q_{2t}(R) = 0.35 \exp(-0.453074\ R/R_{2t}) \tag{3.2-5}$$

$$+0.65 \exp(-2.857143\ R/\bar{R}_{2t})$$

and the annual average Mode 1 and Mode 2 rates $\bar{R}_{1t}$ and $\bar{R}_{2t}$ are very nearly equal to 33.333 and 1.755505 mm/h, respectively. Then $T_1(R)$ may be written as

$$T_1(R) = M \left\{0.03\ \beta \exp(-0.030R) + 0.21(1-\beta)\ [\exp(0.258R) \right. \tag{3.2-6}$$

$$\left. + 1.86 \exp(-1.63R)]\right\} \text{ h.}$$

Use of this relation allows normalized cumulative time distributions to be calculated. Figure 3.2-2 is an example of this result for t=1 minute and B values from 0 to 0.75. Typical values for B and M throughout the US and Canada are given in Figures 3.2-3 and 3.2-4, respectively. Note that the values quoted in Figure 3.2-4 are in inches rather than millimeters required for M. Rice

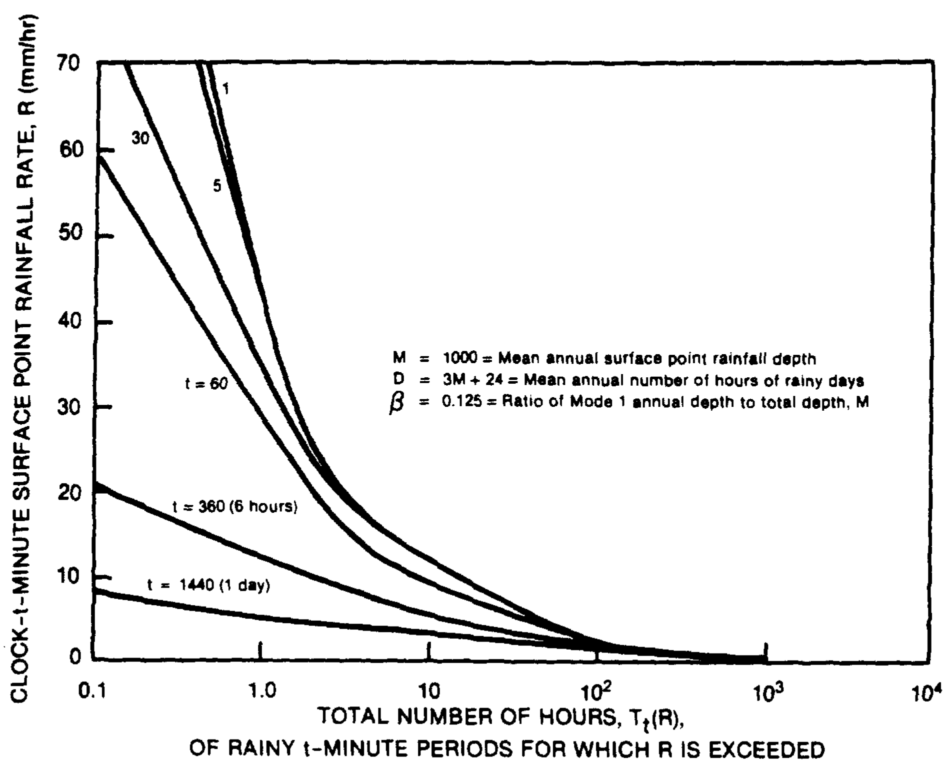

Figure 3.2-1. Average Year Cumulative Time Distributions

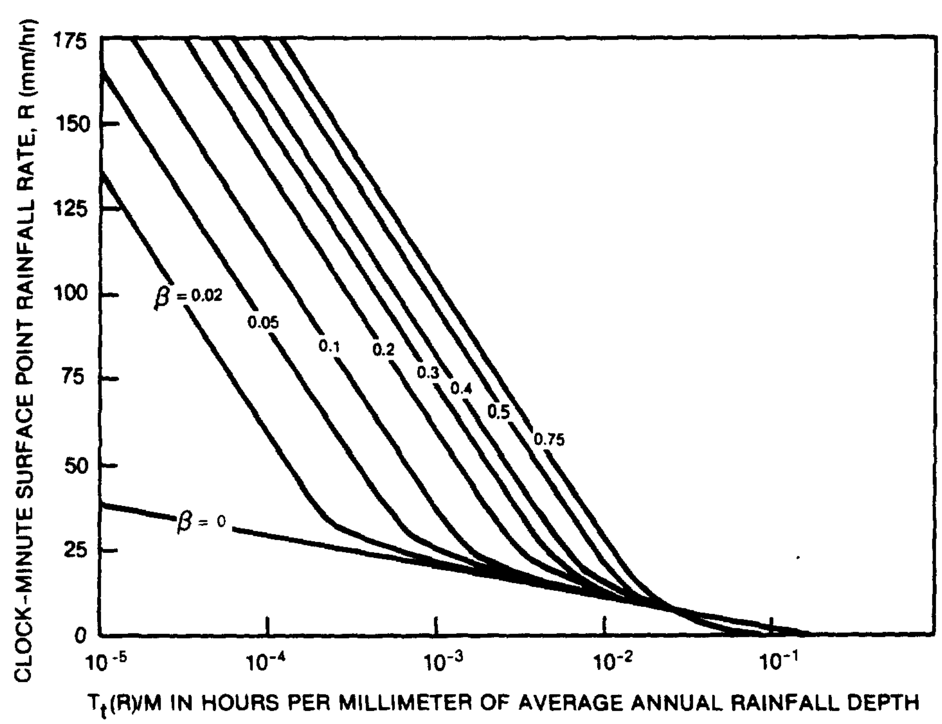

Figure 3.2-2. Normalized Cumulative Time Distributions

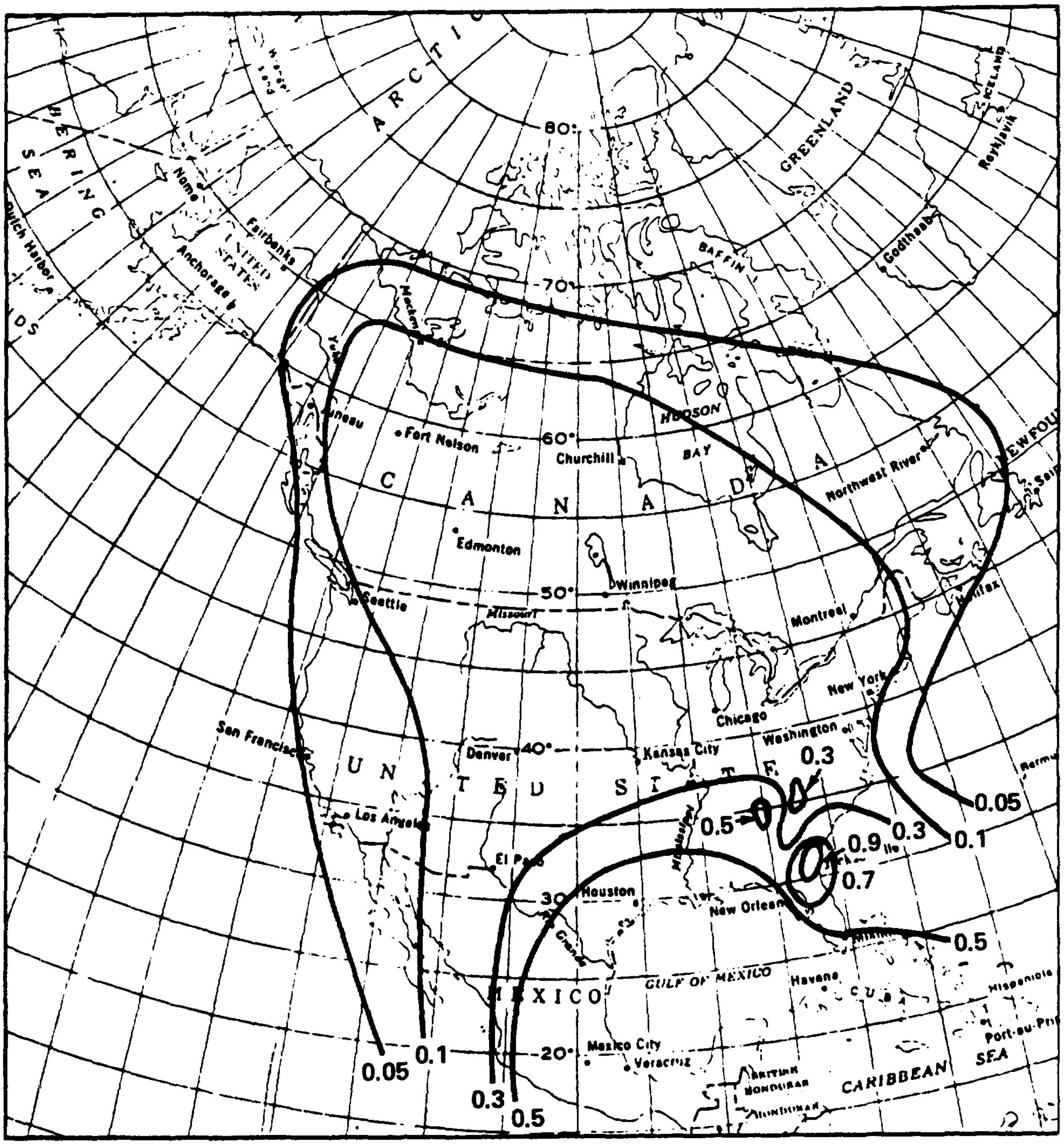

Figure 3.2-3. The Parameter β in the Rice-Holmberg Model Over the U.S. and Canada

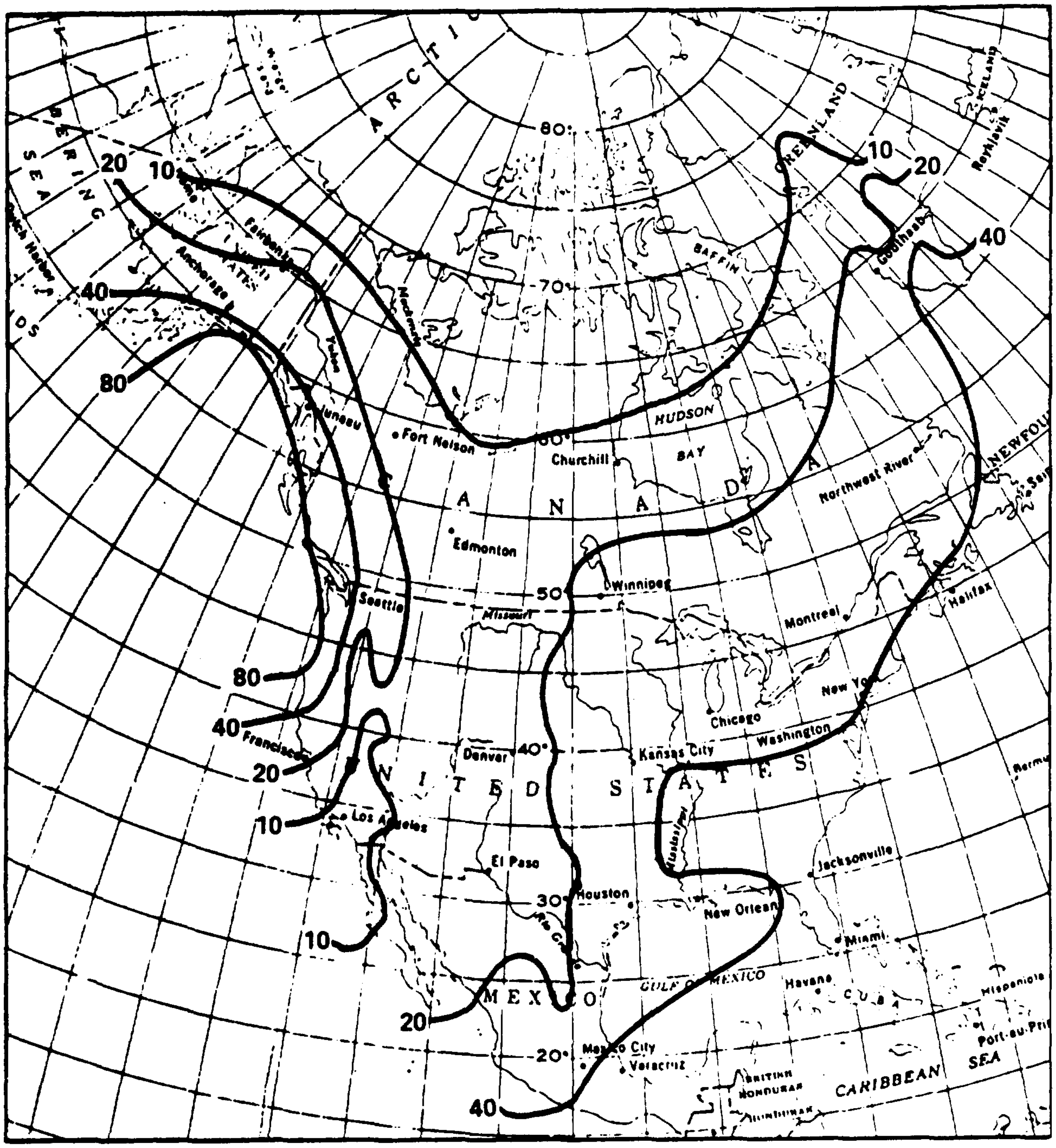

Figure 3.2-4. Mean Annual Precipitation in Inches in U.S. and Canada (1 inch = 25.4 mm)

and Holmberg (1973) have also presented values throughout the world in their original article.

Dutton and Dougherty (1979), (1984), provided a less cumbersome version of the R-H model by fitting relatively simple formulations to various parts of the R-H distribution curve. This "modified Rice-Holmberg model" was applied to a data base of 304 geographically diverse, data intensive locations in the U.S., (including Alaska and Hawaii), and year to year standard deviations of rain rate were developed. The results showed a marked improvement in the bounds of prediction, which appear to encompass the measured data more completely.

These same authors also extended the R-H rain-rate distribution to include a direct prediction of attenuation distributions for specified paths and locations. This attenuation prediction model is the subject of the next section.

3.3 DUTTON-DOUGHERTY MODEL

The Dutton-Dougherty (DD) Model (Dutton and Dougherty-1973, Dutton-1977; Dutton, Kobayashi, and Dougherty-1982) includes attenuation due to both rain and gases. The rainfall rate distributions it uses are based on a series of modifications to the Rice-Holmberg Model (Dutton, et al-1974). The DD Model has been incorporated into a computer program which is available to users from the National Telecommunications and Information Administration. The DD rain and attenuation model components are described separately below.

3.3.1 DD Rain Characterization

The modified Rice-Holmberg (R-H) Model, as used in the DD Model, determines the number of hours of rainy t-minute periods, $T_t(R)$, for which a surface rain rate, R, is expected to be exceeded. The value $T_t(R)$ is given in the modified R-H model as

$$T_t(R) = \begin{cases} T_{1t}\exp(-R/\bar{R}_{1t}) & R \geq R_c \\ (T_{1t} + T_{2t})\exp(-R/R_t') & R < R_c \end{cases}$$

(3.3-1)

with

$$T_{1t} = \beta M/\bar{R}_{1t} \text{ hours} \quad (3.3\text{-}2)$$

$$T_{2t} = (1 - \beta)M/\bar{R}_{2t} \text{ hours} \quad (3.3\text{-}3)$$

Where R_c is a "crossover" rain rate between a convective mode of rainfall ($R \geq R_c$) and stratiform mode of rainfall ($R < R_c$) and other parameters are defined in the R-H Model description. R_T' is a new parameter not used in the R-H Model. This biexponential representation of $T_t(R)$ is strictly analogous to the rainfall conceptions of Rice and Holmberg (1973). From (3.3-1), R_c can be evaluated by setting

$$T_{1t}\exp(-R_c/\bar{R}_{1t}) = (T_{1t} + T_{2t})\exp(-R_c/R_t') \quad (3.3\text{-}4)$$

because it represents the intersection of the two curves in (3.3-1). Thus, we obtain

$$R_c = \bar{R}_{1t}R_t'/(\bar{R}_{1t} - R_t') \ \ln[T_{1t} + T_{2t})/T_{1t}] \quad (3.3\text{-}5)$$

The modified R-H model uses direct estimation of T_{1t}, T_{2t}, $\bar{R}_{1t}$, and R_t' from M, β, and D. This was achieved by using a multiple linear regression to obtain a best fit of T_{2t}, $\bar{R}_{1t}$, and R_t' in terms of of the parameters M, β, and D. It was not necessary to fit T_{1t}, since it is given very simply in terms of M, β, and $\bar{R}_{1t}$ by (3.3-2). The resulting best fits were of the form

$$\bar{R}_{1t} = a_{1t}M + a_{2t}\beta + a_{3t}D + a_{4t} \pm S_1 \quad (3.3\text{-}6)$$

$$T_{2t} = b_{1t}N + b_{2t} \pm S_2 \quad (3.3\text{-}7)$$

$$R_t = b_{3t}M + b_{4t}\beta + b_{5t}D + b_{6t} \pm S_3 \tag{3.3-8}$$

where the coefficients are $a_{1t}...a_{4t}$ and $b_{1t}...b_{6t}$, and the sample standard errors of estimate are $S_1...S_3$.

The third modification is to the portion of the distribution that lies between the rainfall rates of 5 and 30 mm/hour, since two difficulties arise if the equation (3.3-1) is used exclusively for the entire distribution:

1) the transition between curves at R_c is decidedly not smooth, and
2) predictions via (3.3-1) can be noted to be as much as 50 percent below the R-H model in the same vicinity.

In order to partially alleviate these difficulties, it was arbitrarily determined that

$$T_t(R) = T_{st}\exp(-\sqrt[4]{(R/R_{st})} \tag{3.3-9}$$

could be reasonably fit to the data, with proper curvature and simplicity, for $1 \le t \le 60$ min and $5 \le R \le 30$ mm/hour.

For $t > 60$ min (i.e., t=360, 1440 min), the formulation (3.3-1) fits the R-H model sufficiently well over the entire rain rate distribution for operational purposes, so that no additional modification of (3.3-1) is necessary. In summary, then, the resultant modification of the R-H model is:

$$T_t(R) = \begin{cases} T_{1t}\ \exp(-R/\overline{R}_{1t}) & R > 30 \text{ mm/h} \\ (T_{st}\exp(-\sqrt[4]{R/R_{st}}) & 5 \text{ mm/h} \le R \le 30 \text{ mm/h} \\ (T_{1t} + T_{2t})\exp(-R/R_t') & R < 5 \text{ mm/h} \end{cases} \tag{3.3-10}$$

for 1 min $\le t \le$ 60 min. and

$$T_t(R) = \begin{cases} T_{1t}\ \exp(-R/\overline{R}_{1t}) & R \ge R_c \\ (T_{1t} + T_{2t})\exp(-R/R_t') & R < R_c \end{cases} \tag{3.3-11}$$

for $t > 60$ min.

3.3.2 Attenuation Prediction in the DD Model

Dutton (1977) has estimated the variance and confidence levels of the rain rate prediction, and Dougherty and Dutton (1978) have estimated the year-to-year variability of rainfall within a given rain zone. The DD Model attenuation prediction range now extends to 0.001 percent of a year.

Extending the rain model to include attenuation on earth-space paths, Dutton (1977) has assumed the Marshall and Palmer (1948) raindrop distribution. He has also included some degree of modeling of rainfall in the horizontal direction. This is achieved by means of what is termed the "probability modification factor" on earth-space links.

The probability modification factor, F, is given by

$$F \cong \frac{(f/15)^2}{A(f,\theta)} (0.274\Theta + 0.987) \tag{3.3-12}$$

the factor cannot exceed unity, however. In (3.3-12), f is the frequency in GHz, θ is the elevation angle to the satellite in degrees, and $A(f,\theta)$ is the path attenuation in dB. The form was derived from rain storm cell size data given in a particularly useful form by Rogers (1972). The Rogers data, however, were all taken in the vicinity of Montreal, Canada. It would be desirable to have more globally diverse data in order to provide a basis for a more general probability modification factor.

The probability modification factor, applied strictly to attenuation, multiplies the percent of time, P_o , during an average year that a point rainfall rate is expected at a given location. The multiplied value represents the percent of time, P, ($P \le P_o$), that attenuation corresponding to R is expected along the path to a satellite. In effect, a point-to-path rain rate conversion accounting for horizontal inhomogeneity is accomplished.

The probability modification factor given by (3.3-12) applies for exceedance percentages down to 0.01% of a year. The DD model has been extended (Dutton, et al - 1982) to 0.001% of a year by both empirical and analytical means. The empirical extension is simply to make the probability modification factor at 0.001% equal to the value at 0.01%:

$$F(0.001\%) = F(0.01\%) \tag{3.3-13}$$

The analytical extension gives essentially identical results. The extensions recognize that the nature of the very heavy convective rains occurring on the order of 0.001% of the time is different from that of the more "routine" rains of the 0.1% to 0.01% regime.

In the DD model the surface rainfall rate is translated into liquid water content per unit volume, L_o, measured at the ground. The liquid water content at some height, h, above the ground, L(h), can be modeled as a function of L_o (Dutton - 1971). The modeling of L(h) is different for the stratiform and convective rain systems. In the stratiform modeling L(h) is assumed constant to the rain-cloud base, then decreases to zero at the storm top height H. In the convective modeling L(h) increases slightly to the rain-cloud base and then decreases to zero at H, the storm top height.

Attenuation per unit length, $\alpha(f,h)$, due to rain can be calculated from L(h) via expressions of the form

$$\alpha(f,h) = c(f)[L(h)]^{d(f)} \tag{3.3-14}$$

using the data of Crane (1966). Hence, the distinction between the Rayleigh region (f < 10 GHz, approximately) and the Mie region (f > 10 GHz) is implicit, because the coefficients c(f) and d(f) are frequency dependent. In the Rayleigh region, it can be shown that d(f)=1. An interpolation scheme on Crane's data obtains c(f) and d(f) for any frequency in the 10 to 95 GHz region.

Variability of attenuation of earth-space links is, as yet, not directly assessable by theoretical formulation. Thus, it is necessary to input, say, two additional rain rate distributions corresponding to the lower and upper confidence limits of R_o in order to evaluate corresponding confidence limits on an attenuation distribution. This, of course, assumes no variance in the many parameters surrounding the attenuation formulation. This is clearly not so, and indicates that the procedure for evaluating attenuation confidence limits is still in need of refinement.

3.3.3 Dutton-Dougherty Computer Model

Dutton has developed an updated computer program (Steele-1979 and Janes, et al - 1978) to predict the annual distribution of tropospheric attenuation due to rain, clouds and atmospheric gases. Entitled DEGP80, the program also computes the phase delay and reflectivity. The required inputs to the program are:

- Frequency
- Earth station antenna elevation angle
- Identification of data stations
- Height above surface
- Ratio of thunderstorm to non-thunderstorm rain
- Time availability
- Rainfall rate
- Values for average annual atmospheric pressure, humidity, and temperature

The program is valid for frequencies from 1 to 30 GHz and for satellite elevation angles greater than 5 degrees. The program is available from the Institute for Telecommunications Sciences. [See U.S. Dept. of Commerce (1981)].

3.4 THE GLOBAL MODEL

The Global Model has been developed in two forms. Both of these forms utilize cumulative rain rate data to develop cumulative attenuation statistics. The first form, called the Global